

MAGNETOSTATIC MEMS RELAYS FOR THE MINIATURIZATION OF BRUSHLESS DC MOTOR CONTROLLERS

John A. Wright and Yu-Chong Tai

California Institute of Technology, Caltech 136-93, Pasadena, CA 91125, USA

Ph: (626) 395-4861; Fax: (626) 584-9104; email: jaws@mems.caltech.edu

ABSTRACT

Magnetostatic MEMS relays which are capable of commutating the field windings of a DC brushless motor are presented. The commutation system based on these relays is less than 10% the mass and volume of the electronics it replaces, it eliminates all but two wires from the wiring harness, it requires no external control and it dissipates less than 1/1000th the total motor power. Closure forces greater than 5 millinewton are generated in the relays providing four-wire contact resistance readings of less than 35 milliohms. Utilizing gold-to-gold contacts, hot switching of currents greater than 1 amp has been demonstrated. For lifetimes greater than 10 million cycles (greater than 50 hours of continuous motor operation), switched currents should be limited to less than 120 milliamp. At signal levels of less than 1 milliamp, no failure is seen after greater than half a billion cycles. No contact bounce is seen during make or break. Motor commutation in vacuum down to 5 microtorr and from room temperature down to -30 degrees celsius has been demonstrated.

INTRODUCTION

DC electric motors are extensively employed in space born applications as the motive device for linear and rotary drives. Due to the typically DC power bus utilized by most space born vehicles and the difficult and inefficient conversion of DC-to-AC power, AC motors are seldom used. The expensive nature of launching large, heavy equipment out of the Earth's gravity well drives a demand for smaller and lighter components used in spacecraft. Simultaneously, these components must meet or exceed the performance specifications of the parts used in prior missions. In miniaturizing motors, the size, weight and complexity is being dominated by the commutation portion of the system. In brush

motors this means significant motor lengthening as total volume decreases. In brushless motors, the commutation electronics become the main driver of total size and weight. The disparity between motor and controller size becomes excessive in extremely miniaturized motors such as the commercially available 3-mm-diameter presented in [1]. Here, the electronics easily occupy ten times the volume of the motor they are designed to control. By reducing or eliminating the present motor control systems, large gains will be realized in the system-wide design of future spacecraft.

Savings, even small ones, in power budget, complexity, mass and volume of flight instruments have a highly leveraged effect on the total cost and reliability of spacecraft as a whole. For a given set of mission parameters, every savings in one system directly corresponds to larger savings in support systems. Lower power budgets require a smaller power generator (typically solar cells), smaller heat sinks and smaller battery reserves. Reduced instrument size and weight permits the use of a lighter, more compact support frame. All size and weight reductions directly translate into smaller, less expensive booster rockets, higher attainable orbits and/or faster flight times to interplanetary points of interest. Once in space, the reduced mass demands less fuel and power for attitude stabilization and course corrections translating to smaller rockets and gyroscope wheels. Through the miniaturization of DC motors, spacecraft designers will be able to devote more of the limited resources available to the mission goals and less to the systems necessary to place the instruments in their target zone.

Selecting between brush and brushless motor types involves choosing those performance characteristics that are required while minimizing total system complexity, cost and size. Brush motors are typically considered to

have moderate size, weight, power efficiency and complexity and their monetary cost is low. Overall reliability for these motors, however, is poor. For high reliability, brushless motors are chosen. The price for this dependability is an increase in system size, weight, complexity and monetary cost as well as a decrease in power efficiency and low temperature capability. Since a system is only as reliable as its weakest component and since routine maintenance in space is an impossibility at present, spacecraft designers typically hold reliability at a premium. However, the limitations imposed by current rocket and space power generation technologies often override this directive. A prime example of the tradeoffs required can be seen in the design of the Mars rover, Sojourner. Locomotion of this small vehicle was provided by DC brush motors. The power available, the weight permissible and the extreme environment of this mission eliminated the more desirable and reliable option of DC brushless motors.

The magnetostatic MEMS relay based commutation system aims to simplify the control of brushless motors to a level equal to that of brush motors while maintaining the reliability of the brushless system. It is proposed to replace the presently used commutation electronics and position sensors by a single magnetostatic relay for each motor phase. The present experimental system also adds one permanent magnet per pole to the rotating shaft. For space qualified hardware, the relays will be encased inside the motor windings. This location is very attractive because it eliminates the need for any external magnets; the magnets inside the motor provide the actuation force and precise rotor position information to the relays automatically. Since the MEMS relays have nearly negligible size and weight, final system mass and volume is driven by the motor and no longer by the controller. For extremely long life-time

applications, some external arc suppression circuitry may be warranted. With proper design and the use of a silicon substrate, it may be possible to include this circuitry in each relay.

RELAY OPERATION

The magnetostatic relays operate on the principle that a plate made of a magnetic material will tend to align itself in the direction of an external magnetic field. Increasing the external field or the volume of the plate proportionately increases this tendency to align. Equation (1) and its accompanying schematic, figure 1 illustrates the force by the field/plate interaction. DC brushless motors use very strong ($H > 2500$ gauss) magnets in their construction. The fields of these magnets can be tapped to provide actuation forces to device mounted inside the motor and also accurate rotor position information. For this to be possible, however, the volume of any device placed inside the motor must be much less than that of the motor itself. To construct such a device, micromachining is the obvious choice.

Comprised of two electrical contact points held apart by a magnetic plate clamped at one end, the magnetostatic relay is a deceptively simple device. With not external magnetic field present, an air gap between the two electrical contacts is maintained to provide greater than 1000 gigohm isolation (measurement limited by ohmmeter capabilities) and to withstand transient voltages higher than 1000 volts. When placed perpendicularly to an external magnetic field such as pole of a magnet, the free tip of the magnetic plate, which holds one of the electrical contacts, bends down toward the second electrical contact. At the design threshold of the relay, the plate deflects sufficiently to bring the two contacts together to complete an electrical circuit. As the external field increases further, the resistance between the contacts decreases toward its minimum value. Typically this is on the order of tens of milliohms. Removal of the magnetic field permits the restoring force of the bent plate to pull the contacts apart and break the electrical circuit, stopping all current from flowing.

The forces that can be generated in such a device can be very large. Previous work [2-5] has utilized these forces to produce large (millimeter range), out-of-plane deflection devices. For microrelays, such large deflections are not necessary. An air gap of 250 microns readily withstands breakdown when subjected to greater than 2500 volts [6]. Instead of large deflections, large contact forces can be generated which have been shown to minimize contact resistance [7]. Published research [8] indicates that for common contact materials such as gold

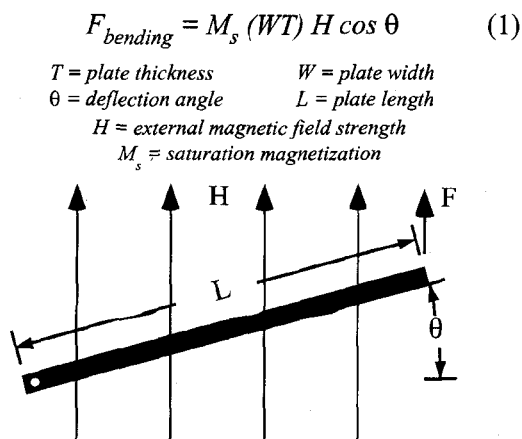


Figure 1. Schematic showing a magnetic plate placed perpendicular to a magnetic field.

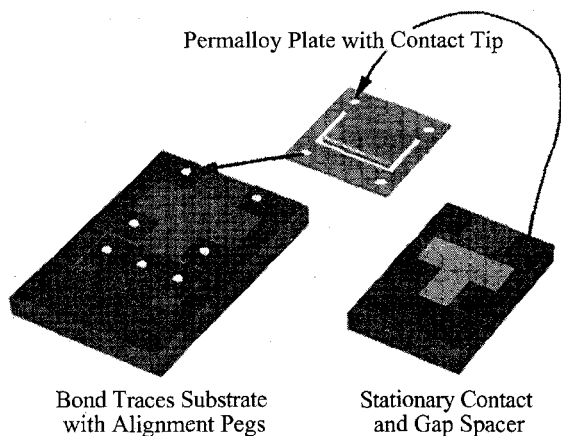


Figure 2. The relay fabrication is completed with the assembly of the three micromachined pieces. Pegs and holes on the parts ensure simple and accurate alignment of the parts.

and silver, contact forces between 100 μN and 1 mN are necessary to minimize contact resistance. Simultaneously, a stiffer magnetic plate can be employed to produce a device with faster switching time, higher g-force tolerance and greater contact break force. Higher break forces increase switching lifetime by permitting stronger contact-to-contact welding points, which can occur during closure, to be broken.

Design of the relay begins with the selection of the magnetic material to be used to fabricate the actuation plate. As equation (1) indicates, M_s should be maximized. Mechanically, the plate should not be brittle, should tolerate large temperature swings and have minimal stress gradients. These parameters are suitably met by permalloy ($\text{Ni}_{80}\text{Fe}_{20}$) which is a soft magnetic metal with $M_s \approx 0.80$ Tesla that can be easily electroplated making it highly compatible with micromachining processes. Use of a soft magnetic material eliminates the need for aligning the magnetic field of the relay plate with the external magnetic field. This simplifies final mounting and permits a wider range relay orientations. For this work, $H = 2500$ gauss and $\theta \approx 0$, values which are dictated by the target motor and the desired contact gap. Performance parameters of the relays resulted in magnetic plate dimensions of $W = 3$ millimeter, $L = 2$ millimeter and $T = 10$ micron. This design produces contact forces in excess of 5 millinewton. The designed air gap of 75 microns results in break forces of just less than 1 millinewton.

FABRICATION

Fabrication may be achieved with either a single substrate or multiple substrate design. For space quali-

fied applications, the increase in mechanical strength possible in a one substrate device will make a monolithic approach most favorable. For research and development purposes, however, the multi-piece design is more attractive. Fabrication from multiple substrates permits non-destructive analysis of relay performance and contact wear. Additionally, it allows the electrical contacts to be formed into more complex and more reliable shapes. For these reasons, a three substrate fabrication process with no critical steps was used. This permitted device yields in excess of 95% to be achieved.

The magnetic plate with integrated contacts are fabricated on the first substrate. Processing begins by forming a sacrificial layer of hard baked photoresist. A second thick layer of photoresist is then spun, patterned and hard baked to create smooth depressions in which the contact points will be subsequently grown. A plating seed layer of Ti/Au (100Å/1000Å) is evaporated and a thick plating (greater than 5 microns) of gold is deposited inside a soft baked photoresist mold. The soft baked mold is removed and 10 microns of permalloy is plated inside a new soft baked mold. Finally, the completed magnetic plate structure is freed by stripping the soft baked mold, the plating seed layer and the underlying hard baked sacrificial resist.

The second substrate processed contains the stationary contact and spacers which define the air gap in the assembled relay. A Cr/Au (100Å/1000Å) seed layer is evaporated on a quartz wafer and 5 microns of gold are plated and patterned to form the stationary contact. This is followed by plating copper through a photoresist mold to form 75 micron tall spacer pedestals. This copper is "dusted" with a thin layer of plated gold to prevent oxidation. The photoresist and underlying seed layer is then stripped, completing the piece.

The third and final substrate of the relay, while not necessary, provides solderable bond traces and an integrated alignment platform for the two pieces described above. It also caps the relay to minimize the debris seen by the contacts and to permit rough handling during experimental testing. From a Cr/Au (100Å/1000Å) seed layer on a quartz wafer, approximately 20 microns of copper is mold plated to form wire traces connected to four large bond pads. On these traces, an additional 20 microns of copper is plated to form alignment pegs. As with substrate two, the copper is "dusted" with plated gold before the photoresist and plating seed layer are stripped.

Final assembly of the three pieces is shown in figure 2. Small dots of solder paste are dispensed onto the

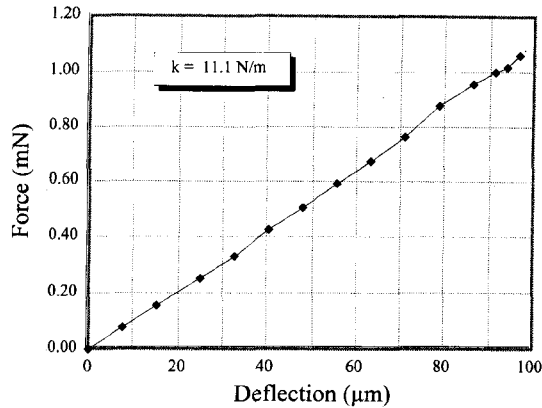


Figure 3. Deflection data for the magnetic plate. Bending force was applied by an external probe.

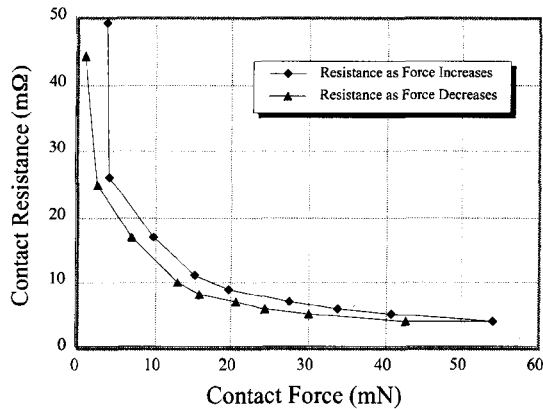


Figure 4. Contact resistance data for relays closed mechanically with an external probe.

alignment pegs of substrate three. The magnetic plate is then sandwiched between this piece and the second substrate. Through-holes in the plate and in the spacer pedestals of substrate two automatically align all three pieces together to ensure proper positioning of the contacts. The parts are lightly clamped together and heated until the solder reflows. Upon cooling, the solder mechanically bonds the three pieces together and provides a high quality electrical connection from the relay contacts out to large bond pads to which wires may be easily attached. By using transparent quartz substrates, relay operation can be readily monitored by microscope, laser or interferometry. The three pieces of the relay can be separated in a non-destructive fashion by simply heating until the solder reflows. This facilitates easy access to the contact regions for wear and failure analysis.

RESULTS AND DISCUSSION

Experimental data detailing switch performance as a function of plate deflection, contact force, contact re-

Relay Hot-Switched Lifetime Testing Results		
Load Switched	Current (mA)	Lifetime (cycles)
Resistive (28 VDC)	0.10	> 500 million
Resistive (28 VDC)	100	1 to 10 million
Resistive (28 VDC)	250	0.1 to 1 million
Resistive (28 VDC)	500	0.01 to 0.1 million
4.2 mH Inductive	250	0.01 to 0.1 million
Motor Commutation	80 to 120	> 20 million

Table 1. Relay lifetimes for a range of operating currents and conditions.

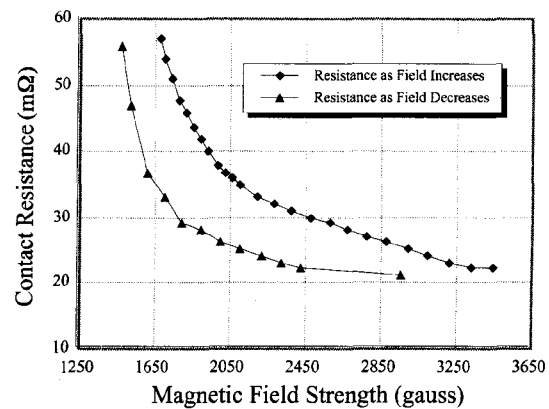


Figure 5. Mechanical deflection data for the magnetic actuation plate used in the relays.

sistance, plate resonance and external magnetic field have been collected. Plate deflection versus bending force data shown in figure 3 verifies linear beam-in-bending approximations. The spring constant calculated from the graph is close to that predicted by theory and results in the desired 1 millinewton range break force for the relays. Figure 4 shows four-wire contact resistance measurements acquired as a function of contact force. As expected, large contact forces of 3-5 mN are required to achieve an $R_{contact}$ of less than 50 milliohms. Note that this is significantly higher than suggested by the data present in [8]. This arises from the fact that the magnetostatic relays employ a contact line, not a contact point. This causes a larger total contact force to be required to attain the contact force per area to minimize the $R_{contact}$. The minimum $R_{contact}$ measured of 1-2 milliohms is only obtained for forces greater than 50 millinewtons. This data may be compared to the plot of $R_{contact}$ versus external magnetic field, H presented in figure 5. Both graphs are very similar, showing the asymptotic behavior of the contact resistance as the force or magnetic field

is linearly increased. As designed, the relays attain a R_{contact} of less than 35 milliohm when H exceeds 2500 gauss.

Performance limits of the relays has been determined by experimental testing. Hot-switching was performed at 100 Hz with an on-duty-cycle of 37%. The lifetime results are summarized in table 1. From this data, it was determined that the gold-to-gold contacts exhibited useable lifetime when switching currents up to 120 mA. For this target motor, relay lifetimes below this current level translates to a minimum of 50 hours continuous motor commutation. All subsequent testing was conducted so as not to exceed this limit. Switching speeds up to 120 Hz, limited by the capability of the test setup not the relays, has been demonstrated. Relay failure is predominately characterized by a drastic rise in R_{contact} on the order of one million ohms. Although infrequent, permanent shorting of the relays due to contact welding is seen.

Examination of relay contacts after being driven to failure shows evidence of melt, splatter and redeposition of metal from one contact to the other. As mentioned above, the relays utilize a ridge, not a point for their contacts. This results in regions of varying wear along the length of the contact line. As is to be expected, the greatest damage is seen at the corners of the plate. Here, evidence of considerable contact melting is readily apparent. Trenches hundreds of microns long and extending down to the insulative substrate is often seen in the stationary contact. Significant redeposition onto the magnetic plate and large splatter and debris zones are seen in these cases. The resulting "pit and spike" struc-

ture is a well documented in literature discussing failure in macroscale relays. These structures explain the high contact resistance seen in relays that did not fail due to contact welding. The large areas of melted material also clearly illustrates that local heating can easily weld the contacts together.

The target motor with three mounted relays is shown in figure 6 next the commutation electronics box being replace. To simplify mounting, the relays are not installed inside the motor as they would be in the final implementation. As such, the motor magnets can not be used as the source of the actuating external magnetic field. Instead, four permanent magnets that generate fields comparable to the motor magnets (approximately 2500 gauss) are attached to an aluminum plate which is mounted to the motor shaft. Fixed to the motor housing, the three relays are positioned at 120 degree intervals around the motor so that they extend over the magnets. With the motor turning, torque ripple is minimized by fine alignment of each relay. Winding currents for this motor range from 80 to 500 mA for DC voltages from 5 to 36 volts at up to 2000 RPM.

Validation of the magnetostatic MEMS relay commutation system was achieved with the successful commutation of the target three phase, four pole DC brushless motor. Initial operation utilized no arc suppression circuitry to protect the relays from the large voltage spike associated with switching the approximately 8 mH inductive load of the motor windings. Regardless, intermittent testing over the course of a day demonstrated commutation up to the motors maximum rotation speed of 2000 RPM. This was followed by several days of

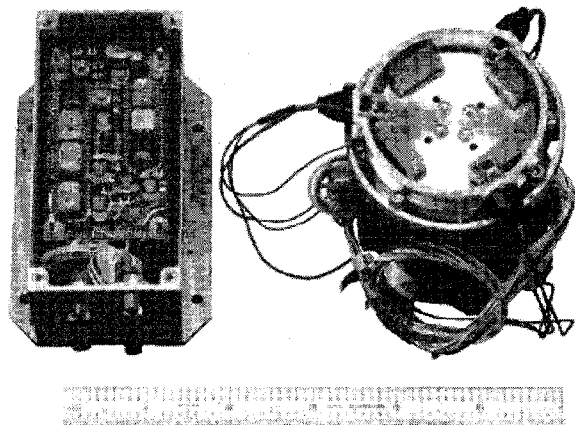


Figure 6. On the right is a three phase, four pole DC brushless motor with three relays mounted on its housing and four magnets fixed to its rotor. To the left is the electronics commutation package being replaced by the MEMS system.

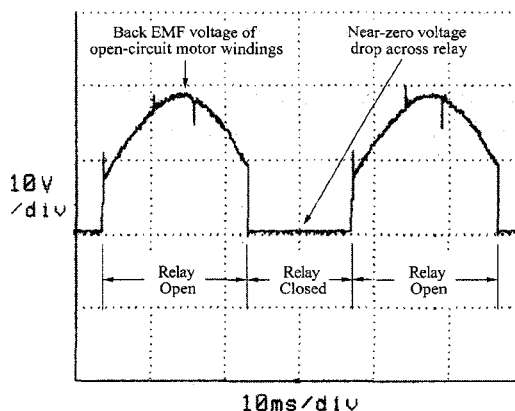


Figure 7. This scope trace shows the voltage across a relay as it commutates a motor. No contact bounce is seen during make and break. The spikes on the back EMF waveform are transients produced as the other two motor windings are switched on and off.

continuous motor commutation at 6 VDC/50 mA. These relays were removed before failure for evaluation of contact wear.

Lifetime and relay performance testing have been conducted under a range of environmental conditions. For these tests, the current switched was kept between 80 to 120 mA and suppression circuitry was added to eliminate inductive arcing. This was done to explore the maximum lifetime of a useful MEMS commutation system for space applications. Testing is still ongoing with the relays have switched more than 20 million cycles at the time this paper went to press. Figure 7 shows a typical switching trace for one relay as it commutates the motor. Note the sharp transitions as the relay opens and closes. No contact bounce is evident. Relay motor commutation has also been demonstrated down to pressures of 5 microtorr and from room temperature down to -30 degrees celsius.

CONCLUSIONS

A magnetostatic MEMS relay based, DC brushless motor commutation system has been realized. Capable of replacing the relatively large and complex electronics packages presently used for commutation, these relays make a new generation of smaller, more efficient and higher reliability motors possible. The present relays, employing gold-to-gold contacts, are capable of commutating motors at up to 36 volts and 500 mA. Maintaining motor currents below 120 mA provide continuous operating lifetimes of several weeks. With proper selection of contact materials, lifetimes should be able to be significantly extended and switching of larger currents made possible.

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